UNIDIRECTIONAL DIVERTOR

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(昭和54年7月25日受理)

Divertors may be necessary for fusion reactors to control the impurities and also provide means of pumping the exhaust. However, the presence of divertors makes the design and maintenance of the reactors rather complex and cumbersome. The divertor coils in the vacuum region is especially problematical. In this note, a divertor where the coil is not in the vacuum chamber is proposed.

The concept utilizes the fact that there is an ion flow parallel to the magnetic field in a tokamak plasma. The mhd equilibrium requires

$$\nabla p = \vec{j} \times \vec{B} \quad (1)$$

Since the toroidal magnetic field is the main field and is proportional to R^{-1} (R : major radius), the perpendicular current is proportional to R . In order to keep the current divergence free, a parallel current $j_{\parallel}$ is given by

$$j_{\parallel} \sim (q \nabla p / B) \cos \theta \quad (2)$$

is produced, where q is the safety factor and θ is the minor azimuthal angle. The direction of the current is parallel to the ohmic current where

$-\frac{\pi}{2} < \theta < \frac{\pi}{2}$ or $R > R_0$ (average major radius). Assuming the ions carry their own diamagnetic current, the flow velocity v of ions is given by

$$v_{\parallel} \sim \frac{qT_i}{eB} \frac{\nabla n}{n} \cos \theta \quad (3)$$

The ratio of the flow velocity over the thermal velocity is given by

$$v_{\parallel}/v_i \sim q(\rho_i/d) \cos \theta \quad (4)$$

where v_i is the thermal velocity and d is the density gradient length.

The motion of the impurity ions is dominated by the drag force due to collisions. They move at the same velocity as the hydrogen ions in the parallel direction. For heavy impurity ions, the flow velocity may be larger than the thermal velocity. The ratio is given by

$$v_{\parallel}/v_i \sim q(\rho_i/d) A^{1/2} \cos \theta \quad (5)$$

where A is the mass number. The flow of impurity ions is, therefore, determined by the flow of the hydrogen ions.

The presence of the parallel flow is confirmed experimentally, at least indirectly, in the ISX flow reversal experiment.⁽¹⁾ Also, the asymmetry of the impurity concentration in the minor azimuthal angle has been observed in Alcator,⁽²⁾ further supporting the existence of the parallel flow.

When a flux surface is interrupted by a limiter or a divertor plate, the flow pattern is determined by two effects, the parallel flow discussed above and the flow to the obstacle. We use the guiding center approximation to calculate the flow pattern. We consider a circular tokamak and place a limiter at $\theta = 0$. The steady state continuity equation is given by

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$$-\frac{1}{r} \frac{\partial}{\partial r} \left(rD \frac{\partial n}{\partial r} \right) + \frac{1}{r} \frac{\partial}{\partial r} \left(r v_r n \right) + \frac{\partial}{\partial s} (v_{\parallel} n) = 0 \quad (6)$$

where D is the diffusion coefficient, v_r is the radial component of the drift velocity and s is the distance in the direction parallel to the magnetic field and is given by $s = Rq\theta$. The radial velocity is given by

$$v_r = \frac{T_i}{eBR} \sin (s/Rq) \quad (7)$$

The equation of motion in the parallel direction is given by

$$m_i n v_{\parallel} \frac{\partial v_{\parallel}}{\partial s} = - (T_i + T_e) \frac{\partial n}{\partial s} \quad (8)$$

where the viscosity terms have been neglected. We put $n = N(r)n_1(s)$ and look for a separable solution. By assuming $d \ll r$, we put $N = N_0 \exp [-r/d]$.

The combination of Equations (5) and (7) yields

$$-d^{-1} v_r + \frac{\partial v_{\parallel}}{\partial s} \left(1 - \frac{m_i}{T_e + T_i} v_{\parallel}^2 \right) = d^{-2} D \quad (9)$$

By integration, we obtain

$$v_{\parallel} - \frac{v_{\parallel}^3}{3 v_s^2} = d^{-2} D (s - \pi Rq) - \frac{qT_i}{eBd} \cos (s/Rq) \quad (10)$$

where $v_s = \sqrt{(T_e + T_i)/m_i}$ and the constant of integration is chosen so that the flow is symmetric in the absence of the toroidal drift. Since $v_{\parallel} \leq v_s$, the cubic equation has one root. The velocities at the obstacle, $s = 0$ and $s = 2\pi Rq$ are given by

$$\begin{aligned}
 v_{\parallel}(o) - \frac{v_{\parallel}^3(o)}{3v_s^2} &= -d^{-2}D\pi Rq - \frac{qT_i}{eBd} \\
 v_{\parallel}(2\pi Rq) - \frac{v_{\parallel}^3(2\pi Rq)}{3v_s^2} &= +d^{-2}D\pi Rq - \frac{qT_i}{eBd}
 \end{aligned}
 \tag{11}$$

The density distribution can be calculated from Equation 7 and is given by

$$n = N \exp \left[-v_{\parallel}^2 / (2v_s^2) \right] . \tag{12}$$

The flux Γ to the obstacle is given by

$$\Gamma = n v_{\parallel} = N v_{\parallel} \exp \left[-v_{\parallel}^2 / (2v_s^2) \right] . \tag{13}$$

Finally, the ratio of the fluxes at $s = 0$ and $s = 2\pi Rq$ is given by

$$\frac{\Gamma(2\pi Rq)}{\Gamma(o)} = \frac{\left| v_{\parallel}(2\pi Rq) \right| \exp \left[-v_{\parallel}^2(2\pi Rq) / (2v_s^2) \right]}{\left| v_{\parallel}(o) \right| \exp \left[-v_{\parallel}^2(o) / (2v_s^2) \right]} \tag{14}$$

In the PLT experiments⁽³⁾ with a surface probe, a difference of $1.5 \sim 2$ in the ion fluxes at the ion and the electron side of the probe has been observed. The ratio is more or less independent of ion species. The approximate parameters are $B \sim 3T$, $q \sim 6 T_i \sim 400$ ev and $d \sim 2 \times 10^{-2}$ meter. If we assume $T_e \ll T_i$ because of conductive cooling, we have $v_s \sim 1.3 \times 10^5$ m/sec and $q T_i / (eBd) \sim 4 \times 10^4$ m/sec. These values are consistent with the observed ratio of the ion fluxes.

The parallel flow may be enhanced by an unidirectional neutral beam injection. It has been observed in PLT experiments that the plasma rotates in the toroidal direction when the neutral beam is injected in one direction.

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For the co-injection, the direction of rotation is parallel to the ohmic current and it enhances the ion flux ratio at $\theta = 0$. The rotation of the central part of the plasma is transmitted to the edge of the plasma by the velocity. The measurement in PLT experiments shows that the rotational velocity at the edge is several times 10^4 m/sec. This value is comparable to the value for $qT_i/(eBd)$.

For the impurity ions, not only the fluxes are asymmetric but, also, the energy of ions are. They travel at a velocity close to that of hydrogen flow. If the flow velocity of hydrogen is close to the sound velocity, the energy of the impurity ion of the mass Number A is roughly A times hydrogen temperature. There is concern that the sputtering due to high energy impurity ions may lead to an unacceptable impurity level. Since the energy of impurity is proportional to the square of flow velocity, the ratio of energy at $s = 2\pi Rq$ and $s = 0$ is given by $(v_{\parallel}(2\pi Rq)/v(o))^2$. The sputtering yield is significantly reduced at $s = 0$, if $|v(o)| < |v_{\parallel}(2\pi Rq)|$.

We consider the design of a divertor by taking advantage of the asymmetric flow. The design shown in Figure 1 is the simplest case of a circular cross-section tokamak, although one can design for tokamaks of non-circular cross-section. The divertor section is on the median plane and outside (major radius wise) of the plasma. The divertor coil is not in vacuum. The divertor plate and the pumping ports are on the side of the preferred ion flow. The other side has a limiter plate.

We define δ as a fraction of the ion flow hitting the limiter. It is given by

$$\delta^{-1} = 1 + \frac{\Gamma(2\pi Rq)}{\Gamma(o)} \quad . \quad (14)$$

Figure 1

Near the separatrix q is large and δ is expected to be much smaller than the value for PLT which is about $1/3$. The system behaves as a limiter for a fraction δ and as a divertor for a fraction $(1-\delta)$.

A divertor serves two functions, one is for pumping the exhaust, the other is to minimize the impurity production and the impurity transport towards the plasma. For the pumping, the proposed system is almost as good as a regular divertor. The impurity production has two sources, i.e., the wall and the limiter. The high energy hydrogen ions will charge exchange with neutral background gas and strike the wall. The sputtering will produce the impurity atoms that enter the plasma. The production rate depends on the charge exchange rate, therefore, the neutral gas pressure near the

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edge of the plasma. The sputtering on the limiter also produces the impurity atoms. The production rate J of the impurity atoms is given by

$$J = \Gamma_0 Y_0 + \Gamma_i Y_i \delta \quad (15)$$

where Γ_0 is the neutral hydrogen flux, Y_0 is the sputtering yield for the neutral hydrogen on the wall, $\delta\Gamma_i$ is the ion flux to the limiter and Y_i is the sputtering yield on the limiter. The ion flux is given by

$$\Gamma_i = nV/\tau_p \quad (16)$$

where V is the plasma volume and τ_p is the particle confinement time. The neutral flux Γ_0 will depend on the neutral gas pressure. The sputtering yields Y_0 and Y_i are sensitive functions of particle energy. The minimization of the production rate may be accomplished by the edge cooling, that is, trading off Γ_0 and Y_i by adjusting the neutral gas pressure.

The impurity pumping rate P is given by

$$P = \Gamma_i (1-\delta) f (1-\Delta) \quad (17)$$

where f is the fractional impurity concentration and Δ is the fraction of gas backstreaming from the divertor to the plasma. By equating the pumping rate and the production rate, we obtain

$$\Gamma_0 Y_0 + \Gamma_i Y_i \delta = \Gamma_i (1-\delta) f (1-\Delta) \quad (18)$$

For the system to be any use, we have to have

$$f > \frac{Y_1 \delta}{(1-\delta)(1-\Delta)} \quad (19)$$

The regular divertor corresponds to $\delta = 0$. Therefore, if Equation 19 is well satisfied, the present system is as good as the regular divertor. For example, if we choose $\delta = 0.2$, $\Delta = 0.2$ and $Y_1 = 2 \times 10^{-3}$ (400 ev proton on stainless steel), we have $f > 6 \times 10^{-4}$. By allowing $f \sim 5 \times 10^{-3}$, the inequality (Equation 19) is well satisfied and the system works as a divertor. The above choice of the values for parameters is somewhat arbitrary. The performance of the system should be studied experimentally.

The magnetic configuration of the system may raise the question of mhd stability. Near the separatrix, the plasma is in a magnetic hill (antiwell). The configuration is similar to the divertor for JT-60. The mhd stability question was studied and was concluded that it will not cause problems.

In conclusion, the proposed system is likely to serve both functions of a divertor, i.e., pumping and impurity control. The advantage is the absence of the divertor coil in vacuum. The coil is outside of the wall and may be treated similarly with the shaping coils. An experimental confirmation is needed before it can be incorporated in a fusion reactor.

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